BERKELEY LAB RESEARCH HIGHLIGHT
MATERIALS SCIENCES DIVISION 02-02

Frustrated Superconductors Get Disorderly

Nanoscale Imaging Depicts Granular Nature of Superconductivity

As reported in the January 24, 2002 issue of *Nature*, a research team led by J. C. Séamus Davis has used scanning tunneling microscopy (STM) to “draw” the first nanometer-scale maps of the "granular" nature of a high temperature superconductor.

The highest known superconducting transition temperatures, T_C, are achieved with cuprate ceramics. Normally, the material is insulating but it can become superconducting if it is “doped” with other atoms. For example, additional oxygen (δ in the formula) in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), introduces positive charges or 'holes' in the cuprate layers which makes the material superconducting. Specific levels of dopants are required and are different depending on the compound.

“Underdoped” cuprates, in which the degree of doping is below the level required for the highest T_C, had been predicted to exhibit “frustrated electronic phase separation” (FEPS). Here the superconductivity does not vanish uniformly in the crystal as the temperature exceeds T_C. Instead, small areas of the sample continue to superconduct but are separated from each other by insulating areas. Furthermore, it was predicted that if the superconducting regions could “contact” each other via “tunneling” the material as a whole would exhibit “granular” superconductivity; that is, the sample would superconduct even though not all of the material was in the superconducting state, as it is in normal superconductivity. Although there was some indirect experimental evidence to support the existence of FEPS in underdoped cuprates, it had never been observed directly.

To examine FEPS at the nanoscale, the Berkeley team used a highly sensitive, cryogenic Scanning Tunneling Microscope designed specifically for studies of high-T_C materials (MSD Highlight 00-3). The team used cleaved perfect single crystals of Bi-2212, which split cleanly along the bismuth-oxygen plane that lies over the copper-oxygen plane, and examined them at 4 K in ultrahigh vacuum. The STM was able to image both individual atoms in the plane and the electronic states of the underlying copper-oxygen plane. By studying changes in the current reaching the STM tip as a function of the voltage between the tip and the surface, two kinds of regions with different conductance were observed: “alpha” regions exhibiting the relatively small “energy gaps,” typical of superconductivity; and “beta” regions with larger gaps. Additional work using small amounts of Ni as “marker atoms” proved that the alpha regions are, in fact, superconducting. From these spectral scans, "gapmaps" (see figure) were constructed showing that, in the underdoped crystal, the alpha regions are roughly circular areas less than three nanometers across, separated from one another and surrounded by narrow beta regions approximately two nanometers wide. As the degree of doping is increased, Bi-2212 displays more interconnected alpha regions, but some isolated beta (insulating) regions remain.

The electronic disorder observed here develops in single crystal material even though it is not granular at all in the structural sense. Moreover, the results show that both superconducting and non-superconducting regions can coexist in the same material although they separate from each other, like oil and vinegar in salad dressing.

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K. M. Lang, V. Madhavan, J. Hoffman, E.W. Hudson, H. Eisaki, S. Uchida, and J.C. Davis, "Imaging the granular nature of high-Tc superconductivity in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$," Nature 415, 412 (2002).

This work was supported by the LDRD program of the Lawrence Berkeley National Laboratory, by the Office of Naval Research, by the Collaborative University of California Los Alamos Research (CULAR) program, by the Miller Research Foundation (J.C.D.), by IBM (K.M.L.), by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science, by a Center of Excellence (COE) grant from the Ministry of Education, Science, Sports and Culture of Japan, and by an International Joint Research Grant from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.